SF 298 MASTER COPY   KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
December 1996

3. REPORT TYPE AND DATES COVERED
Technical

4. TITLE AND SUBTITLE
Energy Absorption for Short Duration Impacts

5. FUNDING NUMBERS
DAAH04-96-1-0082

6. AUTHOR(S)
M. Ziejewski, B. Anderson, M.B. Rao and M. Hussain

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Center for Multivariate Analysis
417 Thomas Building
Department of Statistics
Penn State University
University Park, PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER
96-14

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30529.94-MA-SDI

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

19970212 093

13. ABSTRACT (Maximum 200 words)

The objective of this study is to relate energy absorption characteristics to selected material properties and to establish a methodology that allows one to determine some of the material properties for maximum energy absorption. The finite element program DYNA-3D and its associated pre and post processors were used. The model used is a hollow square column. Five properties of the materials were included in the analysis: (i) Density (ii) Elastic Modulus (iii) Tangent Modulus (iv) Yield Strength, and (v) Poisson Ratio. The Response Surface Method in conjunction with the canonical analysis were employed to locate the optimum or near optimum levels of the properties and then to determine the equation of the response surface in an area near the vector of optimum levels. For the given levels of three out of five material properties used in the study, one can calculate the remaining two material property levels to achieve the near-optimal energy absorption.

14. SUBJECT TERMS

15. NUMBER IF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500   DTIC QUALITY INSPECTED 3   Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18 298-102

ENERGY ABSORPTION FOR SHORT DURATION IMPACTS

M. Ziejewski, B. Anderson, M.B. Rao and M. Hussain

Technical Report 96-14

December 1996

Center for Multivariate Analysis
417 Thomas Building
Penn State University
University Park, PA 16802

Research sponsored by the Army Research Office under Grant DAAHO4-96-1-0082. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

Typeset by $\mathcal{A}_{\mathcal{M}}\mathcal{S}$-TEX

ENERGY ABSORPTION FOR SHORT DURATION IMPACTS

by

M. Ziejewski, N. Anderson, M.B. Rao[1] and M. Hussain

North Dakota State University

ABSTRACT

The objective of this study is to relate energy absorption characteristics to selected material properties and to establish a methodology that allows one to determine some of the material properties for maximum energy absorption. The finite element program DYNA-3D and its associated pre and post processors were used. The model used is a hollow square column. Five properties of the materials were included in the analysis: (i) Density (ii) Elastic Modulus (iii) Tangent Modulus (iv) Yield Strength, and (v) Poisson Ratio. The Response Surface Method in conjunction with the canonical analysis were employed to locate the optimum or near optimum levels of the properties and then to determine the equation of the response surface in an area near the vector of optimum levels. For the given levels of three out of five material properties used in the study, one can calculate the remaining two material property levels to achieve the near-optimal energy absorption.

Key Words and Phrases: Energy absorption, Density, Elastic modulus, Tangent modulus, Yield strength, Poisson ratio, Response surface, Canonical analysis.

[1]The research work of M.B. Rao is supported by Army Research Office Grant DAAH04-96-1-0082

DTIC QUALITY INSPECTED 3

Energy Absorption for Short Duration Impacts

Mariusz Ziejewski, Beth Anderson, Marepalli Rao, and Manzoor Hussain
North Dakota State Univ.

ABSTRACT
The objective of this study is to relate energy absorption characteristics to selected material properties and to establish a methodology that allows one to determine some of the material properties for maximum energy absorption. The finite element program DYNA-3D and its associated pre and post processors were used. The model used is a hollow square column. Five properties of the materials were included in the analysis: (i) Density (ii) Elastic Modulus (iii) Tangent Modulus (iv) Yield Strength, and (v) Poisson Ratio. The Response Surface Method in conjunction with the canonical analysis were employed to locate the optimum or near optimum levels of the properties and then to determine the equation of the response surface in an area near the vector of optimum levels. For the given levels of three out of five material properties used in the study, one can calculate the remaining two material property levels to achieve the near-optimal energy absorption.

INTRODUCTION
To design safer automobiles, knowledge of the energy absorption characteristics of the materials used in the structural elements of the automobile is very important. There is a substantial number of publications which discuss the theory behind and the experimental results of the structural collapse of hollow-thin walled square tubes (McNay, 1988; Mahmood et.al., 1981; Mahmood et.al., 1988, Schmueser et.al., 1988; Tundermann, et.al., 1975). However, there is limited information on the relationship between the energy absorption characteristics of materials and their properties.

The general objective of this study is to relate energy absorption characteristics to selected material properties.

Specifically:
1. To establish the energy absorption for selected materials.
2. To develop a prediction equation that is capable of determining energy absorption based on density, modulus of elasticity, tangent modulus of elasticity, Poisson's ratio and yield strength.
3. To establish the level of the selected material properties for maximum energy absorption.
4. To establish a methodology that allows one to determine some of the material properties for maximum energy absorption.

NUMERICAL ANALYSIS USING DYNA-3D
For this analysis, the finite element program DYNA-3D and its associated pre and post processors were used on an IBM RS 6000 Model 970 running AIX version 325.

The pre processor used for mesh generation was INGRID version 1992a (Christon and Dovey, 1992). DYNA-3D version 3.3.5, which is an explicit analysis code intended for dynamical impact and crash analysis was utilized (Whirley and Engelmann, 1993). The post processor for the graphical output and analysis was TAURUS revision 3.0.92 (Spelce, 1991).

MODELING DETAILS
The model represents a column, made of 1..5 mm thick sheet metal, 304.8 mm long and having square cross-section outside width dimension of 69.9 mm. Load was applied to the upper 50.8 mm of the column as a constant velocity field which acts in a direction parallel to the column's longitudinal axis.

The most unstable stage of the buckling is the initiation of lateral deflection. This is numerically stabilized in the model by using a small crease or initial displacement in the column at the interface between the upper and lower portions. This crease starts the buckling in a predetermined direction, thus eliminating the initial numeric instability.

The column contained two planes of symmetry along the axis of crush. Therefore the crush behavior could be predicted with a quarter model. A uniform mesh was used in the analysis which consisted of 1800 four node shell elements

using three integration points through the thickness. The mesh used 900 elements for each side of the quarter sector: 10 elements for the flange width and 90 elements for the flange length. Initial studies indicated that this high density mesh was necessary to capture the behavior of the corners and hence the behavior of the column as a whole.

The boundary conditions were specified in the following manner. Symmetry boundary conditions were enforced such that the quarter model might represent the symmetric behavior of the full physical column. Note that the column beam walls fold onto themselves in a distorted sinusoid pattern. To prevent the contacting surfaces from penetrating each other a slide surface was defined. The particular slide surface used was the single surface contact (type 4) slide surface. The key feature of this type of slide surface is that every node in the definition is a slave to all other nodes. The advantage to using this type of slide surface lies in the fact that any portion of the defined area can contact any other portion without undesirable penetration. The fixed end of the tube was constrained in all six degrees of freedom to prevent rigid body motion when loaded. The moving end of the column was constrained in five degrees of freedom the remaining degree of freedom along the longitudinal axis of the column was left unconstrained so as to simulate the moving head of a hydraulic press. All nodes on the moving end, were given a constant velocity of 6934.2 mm/sec to crush or collapse the column. The material model used was bilinear elastic/plastic with isotopic hardening.

TEST MATERIALS

Materials used in the numerical analysis are given in Table 1. Five properties of the materials were used : (i) Density (ii) Elastic Modulus (iii) Tangent Modulus (iv) Yield Strength, and (v) Poisson Ratio.

The range of the test material properties were:

Density (kg/cm^3)	0.0018 to 0.0091
Elastic Modulus (GPa)	44.8 to 244.8
Tangent Modulus (MPa)	96.7 to 4468.8
Yield Strength (MPa)	27.6 to 910.1
Poisson's Ratio	0.264 to 0.35

STATISTICAL ANALYSIS OF ENERGY ABSORPTION

The main objective of the statistical analysis was to locate the optimum or near optimum levels of the properties and then to determine the equation of the response surface in an area near the vector of optimum levels. The Response Surface Method in conjunction with the canonical analysis was used to maximize the energy absorption on the basis of the five selected material properties. The Response Surface Method which was first developed and described by Box and Wilson (1951) is used extensively in the field of industrial research. Box and Wilson discussed the Steepest Ascent Method in the search for the near-stationary region surrounding the optimum and this method was useful here in searching for optimal conditions.

The Energy Absorption was defined as the response variable and the other five variables as independent variables or controlled variables.

All the variables have been scaled up or down in order to bring the values of the variables on par. The following is a description of the scaling that has been carried out.

Variable	Scaling Factor
Energy Absorption	1/10,000
Density	1/1,000
Elastic Modulus	1/1,000,000,000
Tangent Modulus	1/10,000,000
Yield Strength	1/1,000,000
Poisson Ratio	10

In order to determine the equation of the response surface, a simple model based on five independent variables was defined as:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_4 + B_5 X_5 + \varepsilon, \qquad (1)$$

where

Y = Energy Absorption is measured in J,
X_1 = Density of the material is measured in kg/cm^3,
X_2 = Elastic Modulus is measured in Pa,
X_3 = Tangent Modulus is measured in Pa,
X_4 = Yield Strength is measured in Pa
X_5 = Poisson Ratio.

It was assumed that ε is the random error having mean zero and variance σ^2 . The estimates of the B's are to be determined by the method of least squares which minimizes the sum of squares of the errors ε.

Since the preliminary analysis indicated that the surface was not planar, a higher-order equation in the variables was a more suitable model to find the optimal levels of properties. The model was defined as:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_4 + B_5 X_5 + B_{11} X_1^2 + B_{22} X_2^2 + B_{33} X_3^2 + B_{44} X_4^2 + B_{55} X_5^2 + B_{12} X_1 X_2 + B_{13} X_1 X_3 + B_{14} X_1 X_4 + B_{15} X_1 X_5 + B_{23} X_2 X_3 + B_{24} X_2 X_4 + B_{25} X_2 X_5 + B_{34} X_3 X_4 + B_{35} X_3 X_5 + B_{45} X_4 X_5 + \varepsilon . \qquad (2)$$

The time determinations are done using the canonical analysis method.

The canonical method is a method of rewriting a fitted second degree equation by changing the origin such that first-order terms and cross-product terms have been removed. It is also called B canonical form. Box and Draper (1987) have given full details of this procedure. If the determined stationary point is a saddle point it allows considerable choice of operating conditions (Box, 1954).

RESULTS

Typical partial output from a compression test is given in Figures 1 and 2.

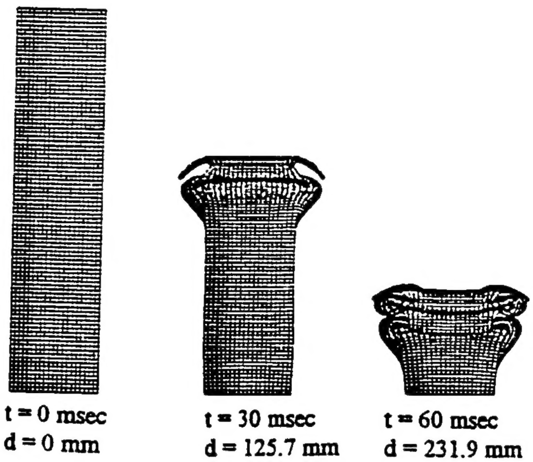

Figure 1. Deformed geometries of column during compression.

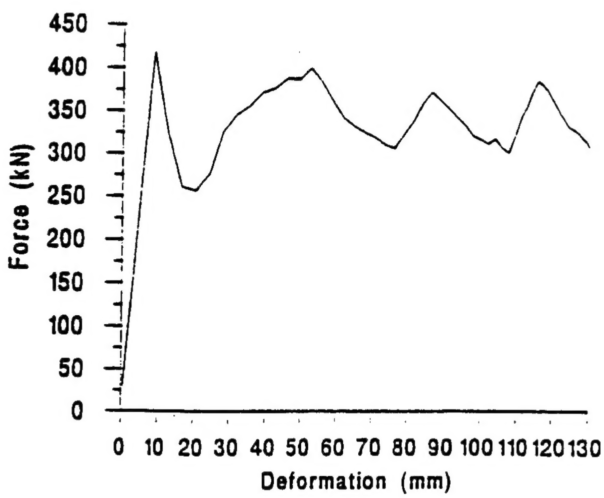

Figure 2. Force-deformation curve of typical column compression.

Using the regression model given above (1) the results are:

$$\hat{Y} = -21.2 - 0.5\,X_1 + 0.1\,X_2 + 0.07\,X_3 + 0.07\,X_4 + 5.6\,X_5 \qquad (3)$$

with F = 691.0 and corresponding p=0.0001 and R^2=0.99.

The Response Surface Model (2) for the given data is:

$$\hat{Y} = 8.3 + 61.9\,X_1 - 2.5\,X_2 + 1.4\,X_3 - 0.2\,X_4 - 9.8\,X_5 + 3.5\,X_1^2 - 0.5\,X_1X_2 + 0.01\,X_2^2 + 0.4\,X_1X_3 - 0.01\,X_2X_3 - 0.0004\,X_3^2 - 0.03\,X_1X_4 + 0.001\,X_2X_4 - 0.00002\,X_3X_4 - 0.00006\,X_4^2 - 16.9\,X_1X_5 + 0.7\,X_2X_5 - 0.4\,X_3X_5 + 0.09\,X_4X_5 + 1.8\,X_5^2, \quad (4)$$

with R^2 = 1.0.

The stationary point T, $x_s = (x_1, x_2, x_3, x_4, x_5)$. The fitted model (4) can be written in the following way:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix}, \qquad (5)$$

$$B = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 61.9 \\ -2.5 \\ 1.4 \\ -0.2 \\ -9.8 \end{bmatrix},$$

$$H = \begin{bmatrix} B_{11} & \frac{1}{2}B_{12} & \frac{1}{2}B_{13} & \frac{1}{2}B_{14} & \frac{1}{2}B_{15} \\ \frac{1}{2}B_{12} & B_{22} & \frac{1}{2}B_{23} & \frac{1}{2}B_{24} & \frac{1}{2}B_{25} \\ \frac{1}{2}B_{13} & \frac{1}{2}B_{23} & B_{33} & \frac{1}{2}B_{34} & \frac{1}{2}B_{35} \\ \frac{1}{2}B_{14} & \frac{1}{2}B_{24} & \frac{1}{2}B_{34} & B_{44} & \frac{1}{2}B_{45} \\ \frac{1}{2}B_{15} & \frac{1}{2}B_{25} & \frac{1}{2}B_{35} & \frac{1}{2}B_{45} & B_{55} \end{bmatrix} =$$

$$H = \begin{bmatrix} 3.5 & -0.2 & 0.2 & -0.01 & -8.5 \\ -0.2 & 0.01 & -0.007 & 0.0007 & 0.4 \\ 0.2 & -0.007 & -0.0004 & -0.00001 & -0.2 \\ -0.01 & 0.0007 & -0.00001 & -0.00006 & 0.05 \\ -8.5 & 0.4 & -0.2 & 0.05 & 1.8 \end{bmatrix}$$

Note that if all the eigenvalues of H are positive, $\hat{Y}$ will be minimum at the stationary point. If all the eigenvalues are negative, $\hat{Y}$ will be maximum at the stationary point. If the eigenvalues are of mixed signs, the stationary point is a saddle point.

Note that λ_i, i=1,2,...,5 are the eigenvalues and m_i, i=1,2,...,5 are the corresponding eigenvectors of the matrix H. For the given problem, the eigenvalues in order of absolute magnitude, and their associated eigenvectors are as follows:

λ_1 = 11.2, m_1=(0.7, -0.04, 0.02, -0.004, -0.7),
λ_2 = -5.8, m_2=(0.71, -0.02, 0.003, -0.004, 0.7),
λ_3 = -0.007, m_3=(-0.03, -0.3, 0.9, -0.1, 0.02),
λ_4 = 0.0003, m_4=(0.03, 0.9, 0.3, -0.3, -0.009),
λ_5 = -0.0, m_5=(0.01, 0.3, 0.2, 0.9, 0.00008).

We write

$$\tilde{X} = \begin{bmatrix} \tilde{X}_1 \\ \tilde{X}_2 \\ \tilde{X}_3 \\ \tilde{X}_4 \\ \tilde{X}_5 \end{bmatrix}$$

$$= M(X - X_s),$$

where

$$M = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{bmatrix}.$$

X is defined in (5) and X_s will be evaluated as

$$-2HX_s = B$$

i.e.,
$$X_s = -\frac{1}{2}H^{-1}B = \begin{bmatrix} 263.4 \\ 6212.5 \\ 5037.7 \\ 20392.5 \\ 5.8 \end{bmatrix},$$

which is called the coordinates of the stationary point.

This gives,

$$\tilde{X}_1 = 0.7X_1 - 0.04X_2 + 0.02X_3 - 0.004X_4 - 0.7X_5 + 2.4 \quad (6)$$

$$\tilde{X}_2 = 0.6X_1 - 0.02X_2 + 0.003X_3 - 0.004X_4 + 0.7X_5 - 2.94 \quad (7)$$

$$\tilde{X}_3 = -0.03X_1 - 0.3X_2 + 0.9X_3 - 0.1X_4 + 0.02X_5 - 6.4 \quad (8)$$

$$\tilde{X}_4 = 0.03X_1 + 0.9X_2 + 0.3X_3 - 0.3X_4 - 0.009X_5 + 20.7 \quad (9)$$

$$\tilde{X}_5 = 0.01X_1 + 0.3X_2 + 0.2X_3 + 0.9X_4 + 0.00008X_5 - 21906.6 \quad (10)$$

The value of $\hat{Y}$ at the stationary point is given by

$$\hat{Y}_s = B_o + \frac{1}{2}X_s' B = 1436.6.$$

There is considerable flexibility in the levels of material properties which can give rise to the value $\hat{Y}_s$. The model $\hat{Y}$ can be written in a new coordinate system as follows:

$$\hat{Y} = \hat{Y}_s + \lambda_1\tilde{X}_1^2 + ... + \lambda_5\tilde{X}_5^2$$

$$\hat{Y} = 1436.6 + 11.2\tilde{X}_1^2 - 5.8\tilde{X}_2^2 - 0.007\tilde{X}_3^2 + 0.0003\tilde{X}_4^2 - 0\tilde{X}_5^2 \quad (11)$$

The dominant eigenvalues are λ_1 and λ_2. The remaining eigenvalues can be ignored. The model can be rewritten as

$$\hat{Y} \cong \hat{Y}_s + 11.2\tilde{X}_1^2 - 5.8\tilde{X}_2^2 \quad (12)$$

Any levels of X_1, X_2, X_3, X_4, and X_5 satisfying

$$\tilde{X}_1 = 0 \text{ and } \tilde{X}_2 = 0.$$

would give the near-optimal value $\hat{Y}_s$. Depending on the given circumstances, the engineers have a good degree of flexibility in choosing the levels of X's.

ENGINEERING APPLICATION OF RESULTS

There are two ways how the results from this analysis can be used by a design engineer:

1. Using equation (3) or (4) one can determine the estimated energy absorption with the knowledge of the selected material properties in this study.

2. Setting the equations (6) and (7) to zero and setting three out of five material properties at desired levels, one can calculate the remaining two variables for near-optimal energy absorption.

For example, for fixed values of density, elastic modulus, and tangent modulus, the information on what value of the yield strength and Poisson's ratio required to obtain the near-optimal energy absorption can be obtained from calculations using equations (6) and (7). If the obtained values for the yield strength or Poisson's ratio are not achievable from a practical point of view, one can change one of the previously fixed properties and see what effect it would have on the values of the calculated properties.

The analysis of equation (12) shows that there is also a possibility of higher energy absorption than calculated by setting equations (6) and (7) to zero. However, the obtained results are beyond the experimental range used in this study.

SUMMARY AND CONCLUSIONS

1. Within the tested experimental range of properties, the developed regression model and response surface model

can be used to determine the energy absorption characteristics.

2. For the given levels of three out of five material properties used in the study, one can calculate the remaining two material property levels to achieve the near-optimal energy absorption.

3. Using the developed technique one can select the easiest achievable combination of the chosen material properties.

4. There is considerable flexibility in the levels of the tested material properties which can assure near-optimal energy absorption.

REFERENCES

1. ASM, "Metals Handbook", Ed. 10, Vol. 2.
2. ASM, "Metals Handbook", Ed. 10, Vol. 3.
3. Boresi, Arthur P., Schmidt, Richard J., Sidebottom, Omar M., "Advanced Mechanics of Materials", Ed. 5.
4. Box, G.E.P. and Wilson, K.B. (1951). On the experimental attainment of optimum conditions. J. Roy. Statist. Soc. B13, 1-38, discussion 38-45.
5. Box, G.E.P. (1954). The exploration and Exploitation of Response Surfaces: Some General Considerations and Examples. Biometrices, 10, 16-60.
6. Box, George.E.P. and Draper, Norman R. (1987). Empirical Model-Building and Response Surfaces. John Wiley & Sons Publishers.
7. Christon, M.A., Dovey, D., "INGRID: A 3-D Mesh Generator for Modeling Nonlinear Systems-User Manual", Lawrence Livermore National Laboratory, September 1992.
8. Mahmood, H. F., Paluszny, A. and Tang, X., "Design of Thin Walled Columns for Crash Energy Management - Their Strength and Mode of Collapse", Society of Automotive Engineers #811302.
9. Mahmood, H. F., Paluszny, A. and Tang, X., "Crash Analysis of Thin Walled Beam-Type Structures", Society of Automotive Engineers #880894.
10. McNay, G.H. II, "Numerical Modeling of Tube Crush with Experimental Comparison", Society of Automotive Engineers #880898.
11. Spelce, T., "TAURUS: An Interactive Post-Processor for the Analysis Codes NIKE3D, DYNA3D, and TOPAZ3D", Lawrence Livermore National Laboratory, May 1991.
12. Schmueser, D.W., Wickliffe, L.E., Mase, G.T., "Front Impact of Primary Structural Components of a Composite Space Frame", Society of Automotive Engineers #88090.
13. Tundermann, J.H., Larson, G.M., Anderson, R.B., "The Application of Elastomeric Buckling columns in an Energy Management Bumper System", Society of Automotive Engineers #750011.
14. Whirley, R.G., Engelmann, B.E., "DYNA3D: A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics-User Manual", Lawrence Livermore National Laboratory, November 1993.